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Using Geophysics to Assess the Condition of Small Embankment Dams

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ABSTRACT: The U.S. Army Engineer Research and Development Center (ERDC) Geotechnical and Structures Laboratory conducted a program of technical and archival research to document current knowledge of indirect seepage detection and methods for monitoring the conditions within small embankment dams. This report documents current methods used to determine conditions within embankment dams by indirect means and provides guidance on determining which methods will most likely succeed at various sites. The report includes a review of current indirect geophysical technologies used in seepage investigations with emphasis on small-sized earthen dams (<7,500 m long, <40 m high). A summary of state-of-the-art equipment, principles of operation, and field procedures is also presented, followed by the results of a September 2003 geophysics-based investigation of seepage and conditions within Clearwater Dam in southeastern Missouri. The report concludes with recommendations for future development of the most promising technologies to be used for seepage detection and assessing the condition within embankments.

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Preface

This report summarizes indirect methods to assess the conditions within embankment dams. It was prepared by the U.S. Army Engineer Research and Development Center (ERDC) for the Federal Emergency Management Agency (FEMA), under Interagency Agreement EMW-2003-IA-0226. Dr. Lillian D. Wakeley, Chief, Chief, Engineering Geology and Geophysics Branch, Geotechnical and Structures Laboratory (GSL), was the ERDC technical point of contact (POC), and Dr. Gene Zeizel was the technical POC for FEMA.

In addition to the summary of methods, this report includes a case history of a geophysical investigation of Clearwater Dam, Missouri, conducted during 2003 in conjunction with the U.S. Army Engineer District (USAED), Little Rock. The cooperation of Mr. Steve Hartung and other professionals at the USAED, Little Rock, was essential to the success of the project.

Mr. Troy R. Brosten, Mr. Jose Llopis, and Ms. Julie R. Kelley performed the field investigation of Clearwater Dam in August-September 2003 and prepared this report. Dr. Wakeley, GSL, also contributed to the report. The work was performed under the general supervision of Dr. Robert L. Hall, Chief, Geosciences and Structures Division, and Dr. David W. Pittman, Director, GSL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James R. Rowan, EN, was Commander and Executive Director.

1 Introduction

Study Description

At the request of the Federal Emergency Management Agency and the Interagency Committee on Dam Safety, the U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory, initiated a program of technical and archival research to document current knowledge of indirect seepage detection and methods to monitor the conditions within small embankment dams. The purpose of this report is to document methods used recently to determine conditions within embankment dams by indirect means. This report includes a review of current indirect geophysical technologies used in seepage investigations with emphasis on small-sized earthen dams (<7,500 m long and <40 m high). A summary of state-of-the-art equipment, principles of operation, and field procedures is presented, followed by results from a September 2003 geophysics-based investigation of seepage and conditions within Clearwater Dam in southeastern Missouri. The report concludes with recommendations for future development of the most promising technologies to be used for seepage detection and assessing the condition within embankments.

Continuous evaluations and monitoring of embankment conditions define the safety level of dam sites. Knowledge of the embankment conditions provides dam management teams with the necessary information to make timely repairs to the dam structure before such areas compromise the dam's structural integrity. All embankment dams are expected to seep to some degree. Anomalously visible water seepage areas may indicate damage to the structural integrity of the dam and require immediate repairs that interrupt normal reservoir operations. Seepage transporting larger amounts of water than anticipated often occurs along preferential paths created by anomalous conditions within the dam. Anomalous conditions include fracture zones, solution channels and cavities, poorly mixed fill in the embankment, and paths created along buried drainage pipes or electrical lines. Technology is now available to characterize and monitor the internal condition of embankments pre-emptively, that is, to identify potential problems early and avoid major dam incidents. This preventive approach could replace large repair costs with timely, small-repair costs promoting cost-effective decisions.

This report summarizes current indirect techniques and presents results of the ERDC study of conditions within a small embankment dam, conducted in September 2003.

Background

There are 75,926 dams in the United States, of which 81 percent are earthen dams. The U.S. Army Corps of Engineers (USACE) is responsible for 569 dams listed from the National Inventory of Dams. From the time the USACE accepted responsibility for these dams, ERDC has provided technical and expert personnel in support of projects initiated to assess embankment conditions. These projects include assessments of site conditions characterizing and locating the presence of seepage and cavities within embankments and foundations.

Between 1935 and 2001, a total of 205 incidents that affected USACE dams were documented. Incidents are defined as a failure; an accident; major rehabilitation; damage during construction, repair, or operational maintenance; or any other noteworthy action outside of normal operations (Dunbar and Villanueva 2005). With dams reaching an average age of 40 years, managers and decision-makers need user-friendly technical information about tools and techniques to reduce uncertainty about dam conditions. This report is intended to provide some of the needed information, by contributing to successful seepage detection and monitoring programs to help prevent future dam failures.

2 Geophysical Methods

Several geophysical techniques are listed below, with explanations of how they apply to seepage investigations. Most of the methods listed could also be applied to foundations, abutments, and large embankments. However, this report focuses on applicability to small dams (<7,500 m long and <40 m high).

Self-Potential

The self-potential (SP) method is a passive technique used to measure small naturally occurring electrical potentials generated by fluid flow, mineralization, and geothermal gradients within the earth. Past seepage investigations have indicated a relationship between SP anomalies[1] and seepage flow (Butler and Llopis 1990, Corwin 1989), with negative anomalies recorded above downward or horizontal flow and positive anomalies recorded above areas with upward seepage flow (Corwin 1989). Anomalous recordings could also result from numerous sources other than seepage flow, such as electrochemical activity created through oxidation reactions, groundwater recharge, and telluric currents, to name a few (Butler and Llopis 1990, Payne and Corwin 1999). However, surveys can be conducted with proper consideration for other sources, leading to appropriate interpretation of seepage anomalies from SP data.

Figure 1 illustrates the concept of an SP survey set up along the crest of a dam and the recorded anomaly caused by seepage flow. For seepage investigations, a single survey line could detect and locate an anomaly caused by a seepage path. For best data quality, fixed-reference SP surveys should be deployed, where measurements are taken between the fixed-base electrode and the measuring electrodes placed perpendicular to suspected seepage flow lines (Corwin 1989). Comprehensive SP investigations include survey data sets gathered at different reservoir levels. Cross-comparing these data sets isolates the SP response to changes in the pattern of seepage (i.e., varying reservoir levels cause different groundwater seepage flow paths and volumes), to reveal the flow path.

The SP method is a cost-effective passive technique that has found an increasing role in geotechnical investigations and has successfully located seepage paths within embankment dams, levees, and reservoir systems (Al-Saigh

[1] A geophysical anomaly is a variation in the data from the values predicted either theoretically or empirically from surrounding values, that is, differences from the signature of the geologic setting potentially indicating a feature of interest.

et al. 1994, Black and Corwin 1984, Butler 1984, Butler and Llopis 1990, Butler et al. 1989, Cooper and Koester 1984, Corwin 1989, Furgerson et al. 1997, Koester et al. 1984, Markiewicz 1984, Nickels et al. 1991, Panthulu et al. 2001, Payne and Corwin 1999, Sirles 1997, Sjostrom and Hotchkiss 1996, Taylor and Lange 1999, Titov et al. 2000). The increasing role of SP has initiated research on SP algorithms to quantify flow volume and to develop the SP technique as a comprehensive investigative tool in seepage assessment projects (Sheffer and Howie 2003).

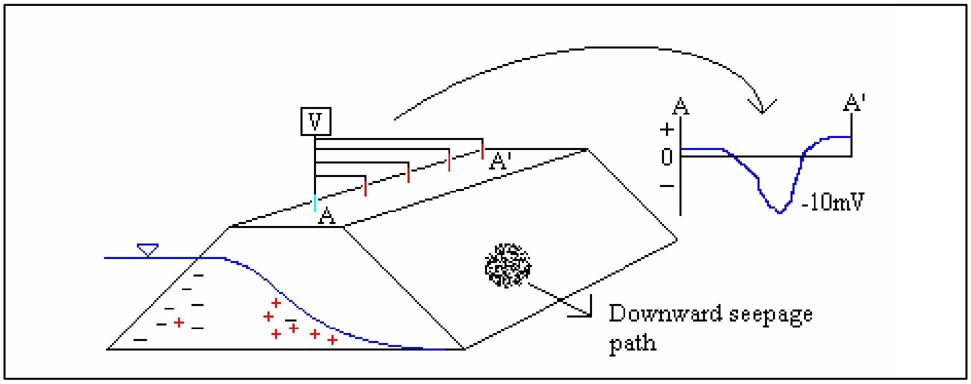

Figure 1. Illustration of an electrode array set up along the crest of a dam and the SP anomaly generated from downward seepage

Electromagnetic Profiling

Electromagnetic (EM) methods are used to measure conductivity differences of geologic material. In the case of seepage studies, possible seepage paths can be located through the identification of high- or low-conductivity anomalies, where water-filled or clay-filled features can produce high-conductivity anomalies and air-filled features can produce low-conductivity anomalies. Subsurface soil types can also be inferred from EM measurements (Dunbar et al. 2003). However, other factors such as porosity, degree of saturation, and temperature can also affect conductivity measurements.

The EM instrument system consists of an electromagnetic loop transmitter and a loop receiver where the transmitter generates a primary electromagnetic field that propagates above and below ground. When the primary EM field encounters a conductive material within the subsurface, alternating currents occur which, in turn, generate their own secondary EM field. The receiver detects the secondary EM field along with the primary field that travels through the air (Figure 2). The ratio between the secondary and primary EM fields provides a comparative reading of the apparent ground conductivity (Reynolds 1997).

Advantages of the EM method include the following: (1) ability to collect data without ground contact, (2) rapid data collection over large areas, and (3) high horizontal resolution, which enables easier anomaly identification through simpler signatures. Disadvantages include these: (1) a limited depth of investigation (typically no greater than 15 ft (4.6 m) for most systems), (2) sensitivity to aboveground and buried metallic objects, and (3) instruments are subjective to interference from nearby alternating current electrical sources (Butler and Llopis 1990).

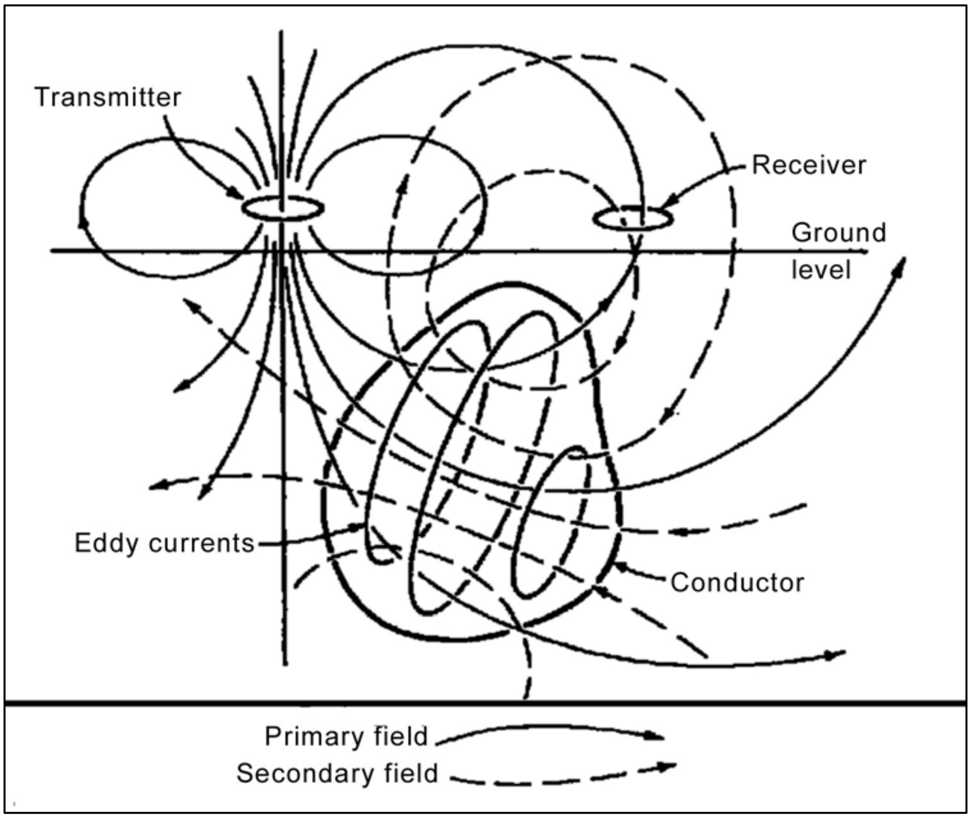

Figure 2. EM surveying method (Grant and West 1965)

Electrical Resistivity Profiling and Sounding

Ground resistivity is related to geologic variations such as the mineralogy, fluid content, porosity, and degree of water saturation in the rock. Electrical resistivity profiling provides a 2-dimensional (2-D) model interpretation of the subsurface resistivity distribution in the vertical and horizontal direction along a survey line. From the 2-D model, a subsurface distribution of the geologic variations can be inferred.

Resistivity surveys are conducted by laying out electrodes along a survey line. Current is introduced into the ground through a pair of current electrodes (C_1 and C_2), and two potential electrodes (P_1 and P_2) measure the voltage difference. As the current and potential electrodes increase in spacing, the depth of investigation also increases. By measuring voltage differences as the electrode spacing increases, a 2-D profile of the subsurface is created. Geological interpretations of the subsurface are then made based on the 2-D profile.

Numerous array configurations can be chosen, with advantages and disadvantages for each one. The best array for the survey is dependent on the type of geologic materials being investigated, the desired depth of investigation, the signal strength, the array sensitivity to vertical and horizontal resistivity changes in the subsurface, and the probable background noise. For seepage investigations, resistivity targets generally include fracture zones and solution features created through preferred seepage paths. Resistivity profiling is a primary method used in seepage investigations and has successfully delineated seepage paths in past studies (Butler and Llopis 1990, Karastathis et al. 2002, Panthulu et al. 2001, Sirles 1997).

Soundings provide a 1-dimensional (1-D) model of true layer resistivity and thickness beneath the center of the electrode array. Past investigations employing vertical electrical soundings (VES) have provided useful information in seepage studies (Abu-Zeid 1994, Butler and Llopis 1990, Gourry and Moldoveanu 1997, Panthulu et al. 2001, Sirles 1997, Titov et al. 2000). However, the method is unable to take into account horizontal changes in the subsurface, which is a limiting factor during the interpretation process.

Ground-Penetrating Radar

Ground-penetrating radar (GPR) uses a high-frequency (50- to 1,000-MHz) EM pulse transmitted into the ground. The radar pulses are reflected from subsurface interfaces possessing a contrast in electrical properties and recorded by the receiving antenna. Such things as soil horizons, groundwater surface, soil/rock interfaces, or man-made objects can cause noticeable dielectric variations.

Previous seepage investigations (Butler and Llopis 1990, Gourry and Moldoveanu 1997, Karastathis et al. 2002) have demonstrated the ability of GPR to provide useful information. Advantages include good spatial resolution and high acquisition speed. However, GPR's primary disadvantage is its extreme sensitivity to site conditions. Areas with high clay or water content within the shallow subsurface can attenuate the GPR signal, making it virtually useless.

Seismic Refraction and Reflection

Active seismic methods require the introduction of energy into the ground at a known time and, then, recording the reflected or refracted returning energy to map the subsurface from the recorded data. Results from seismic refraction methods often aid in determining the depth to competent rock for future remediation efforts (Karastathis et al. 2002). High-resolution seismic reflection methods have allowed vast improvements in data collection techniques over the past 10 years (Inazaki 1999, Inazaki and Kano 2000, Van der Veen and Green 1998, Van der Veen et al. 1999) and have been used to characterize sinkholes in related seepage studies.[1]

[1] R. D. Miller, J. Ivanov, D. R. Laflen, and J. M. Anderson. (2003). "Seismic investigation of a sinkhole on Clearwater Dam," Preliminary Report, Kansas Geological Survey, KS.

Other Methods

Other methods including dye testing, surface seepage water conductivity and temperature measurements, microgravity, magnetic, and microacoustic surveys often act in supporting roles when chosen to be included in seepage investigations. Dye testing and surface seepage water conductivity and temperature measurements can aid in determining the path origin by establishing hydraulic connections between two points (Nickels et al. 1991, Sjostrom and Hotchkiss 1996). Microgravity surveys can aid in locating cavities and characterizing subsurface karst topography. Magnetometer surveys help locate unknown shallow metallic objects (i.e., buried metal pipes, scrap metal, rebar) that can cause flawed interpretations from other geophysical methods. In addition, underwater microacoustic surveys are another passive method used to locate reservoir leaks through detection of low-frequency underwater sounds (Nickels et al. 1991).

Advances in technology have increased usage of geophysical airborne methods including EM, gravity, and GPR for rapid data collection over large areas. A recent collaborative investigation conducted by ERDC and Furgo Airborne Surveys along the flood control levees maintained and operated by the U.S. section of the International Boundary and Water Commission (IBWC) in south Texas found airborne EM methods to be exceptionally useful for characterizing long stretches of levee systems (Dunbar et al. 2003). Currently, usage of airborne methods for characterization of individual small earthen dams would be impractical due to the small sized investigation sites. During the IBWC study, the ERDC team determined that ground-surface EM techniques applied to short reaches of levees found the same anomalies that the airborne method had revealed in the same reaches. This surface-EM work of levee segments approximates surveys of small embankment dams and will be described in the second ERDC report of this series.

3 Case History: Clearwater Dam, Missouri

The U.S. Army Engineer District (USAED), Little Rock, AR, is responsible for daily operations and monitoring of the Clearwater Dam in southeastern Missouri. To aid in ongoing monitoring of subsurface condition and seepage, the Clearwater Dam investigation, conducted in September 2003, was selected as an appropriate case study due to the size of the dam embankment (<7,500 m long and <40 m high) and the use of multiple geophysical techniques. The ERDC Geophysics Team worked with District personnel to design and conduct a geophysical investigation along the dam's downstream toe using SP, EM, and resistivity techniques.

Geologic Setting

Clearwater Dam, located on the Black River in Wayne County, MO, was constructed as part of a comprehensive program for flood control in the White and Mississippi River Basins (USAED, Little Rock 1941). Borehole logs describe the subsurface geology as sandy gravel with thickness ranging between 15 and 40 ft (4.6 and 12.2 m) down to basement rock. The limestone bedrock has been consistently recorded at an elevation depth of approximately 440 ft (134 m).

Dolomitic limestone of the Upper Cambrian Potosi Formation forms the bedrock surface directly below the dam and reservoir. The rocks are flat-lying, jointed, and fractured and contain numerous chert beds. Zones of clay and soft, friable limestone are present as a result of solution weathering. The Eminence Formation, also a dolomitic limestone, comprises the upper part of the lake rim and can be found in the abutments (USAED, Little Rock 1948). The presence of numerous caves and springs in the area as viewed on topographic maps and aerial photos shows evidence of solution activity.

The major system of joints strikes approximately east-west with an almost vertical dip. This presented a concern because enlarged joints in the bedrock beneath the dam could create preferred pathways for seepage leading to embankment instability. Two sets of enlarged joints were discovered during construction: one in the area of the outlet works tunnel and another in the stilling basin. Both were consequently filled with concrete (USAED, Little Rock 1981). Armed with the knowledge of the geology of the area, the District initiated a monitoring program to track anomalous increases in seepage as a pre-emptive measure to avoid irreparable damage to the embankment structure.

Geophysical Surveys and Results

Specific geophysical methods deployed for the Clearwater Dam investigation included self-potential, electromagnetic conductivity, electrical resistivity profiling, and vertical electrical sounding. Figure 3 shows a geo-rectified aerial photograph of Clearwater Dam with the locations and layout of the geophysical survey lines. Selected piezometers and local power lines are included to provide orientation. A localized coordinate system was defined for survey lines along the toe of the dam to be viewed with a downstream orientation (excluding the left abutment EM surveys). Station 00 was selected at the uppermost northeast corner where the left abutment meets with the toe of the dam with stationing increasing to the southwest, except for survey line 5 with stations increasing to the southeast. All survey lines running parallel to the toe of the dam were tied into station 00 for correlation among the various geophysical techniques used in the investigation.

Figure 4 displays the geophysical test layout with a 50-m grid overlaying the test area. Station 00 is located at the northeast end of all survey lines trending along the toe. Station 00 for survey line 5 (survey line running southeast along the left abutment) has the same starting point as survey line 1. Locations for the power lines, selected piezometers, reference SP electrode, manhole covers, buried corrugated metal pipe system, VES, and a buried power line were included in the survey layout for reference.

Self-potential

Figure 5 presents morning and evening SP readings recorded over a 2-day period for SP readings taken on survey line 1. Interpretation involved identifying zones of negative SP values that may indicate probable paths of seepage in the downstream direction. Line 1 shows anomalous lows centered at stations 50, 90, 130, 160, 220, 240, and 280. Stations 90 and 280 represent the largest amplitude SP anomalies (up to 100 mV) that could be an indication of greater flow when compared with the remaining smaller magnitude anomalies. These apparent high-flow zones may be associated with buried shallow faults or fracture zones. However, the anomaly located at station 90 is most likely related to a buried 6-in. (152-mm) drainage pipe crossing the survey line near station 75. A preferred seepage path seems to have developed near the vicinity of the pipeline.

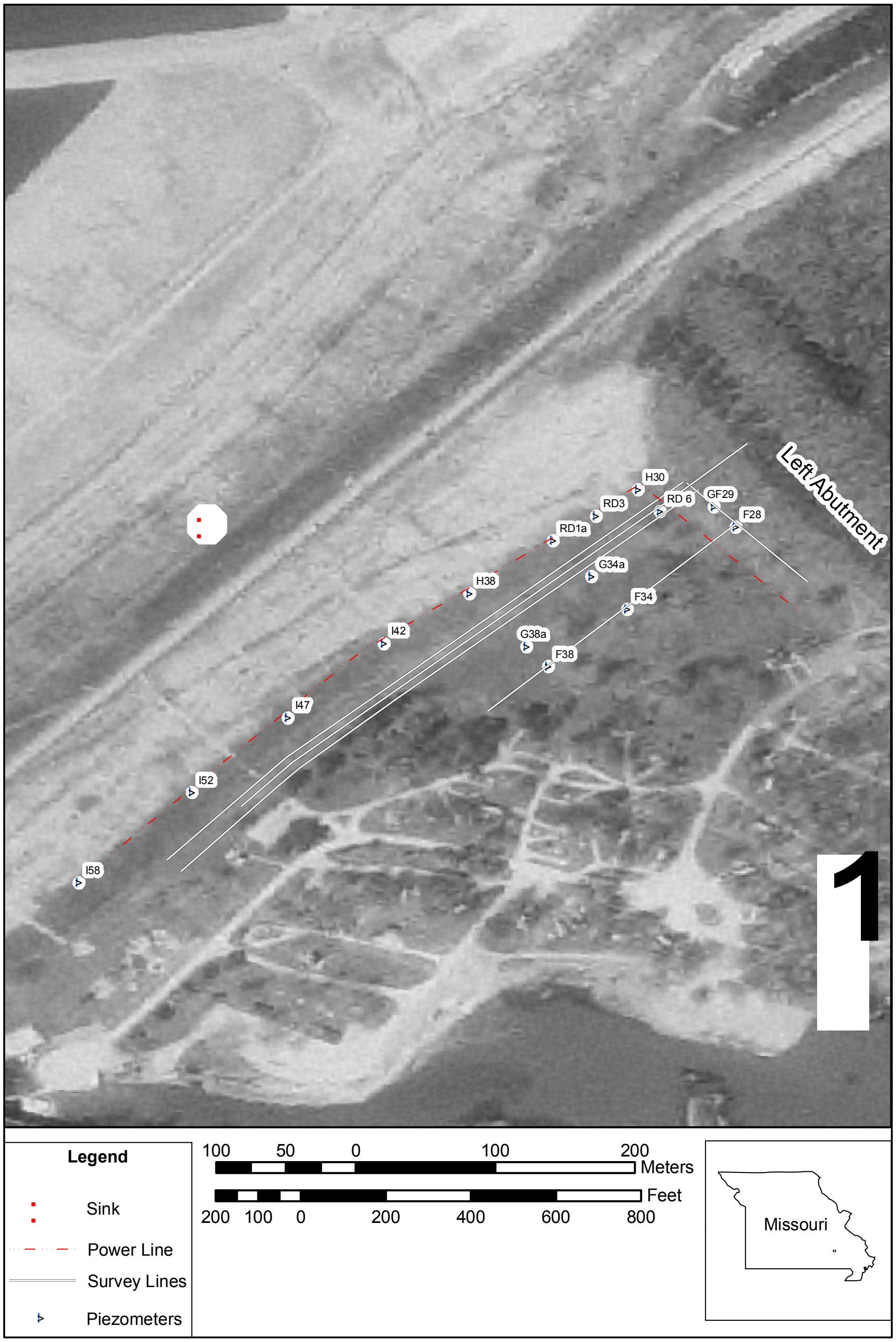

Figure 3. Locations of geophysical surveys, selected piezometers, power lines, and sinkhole

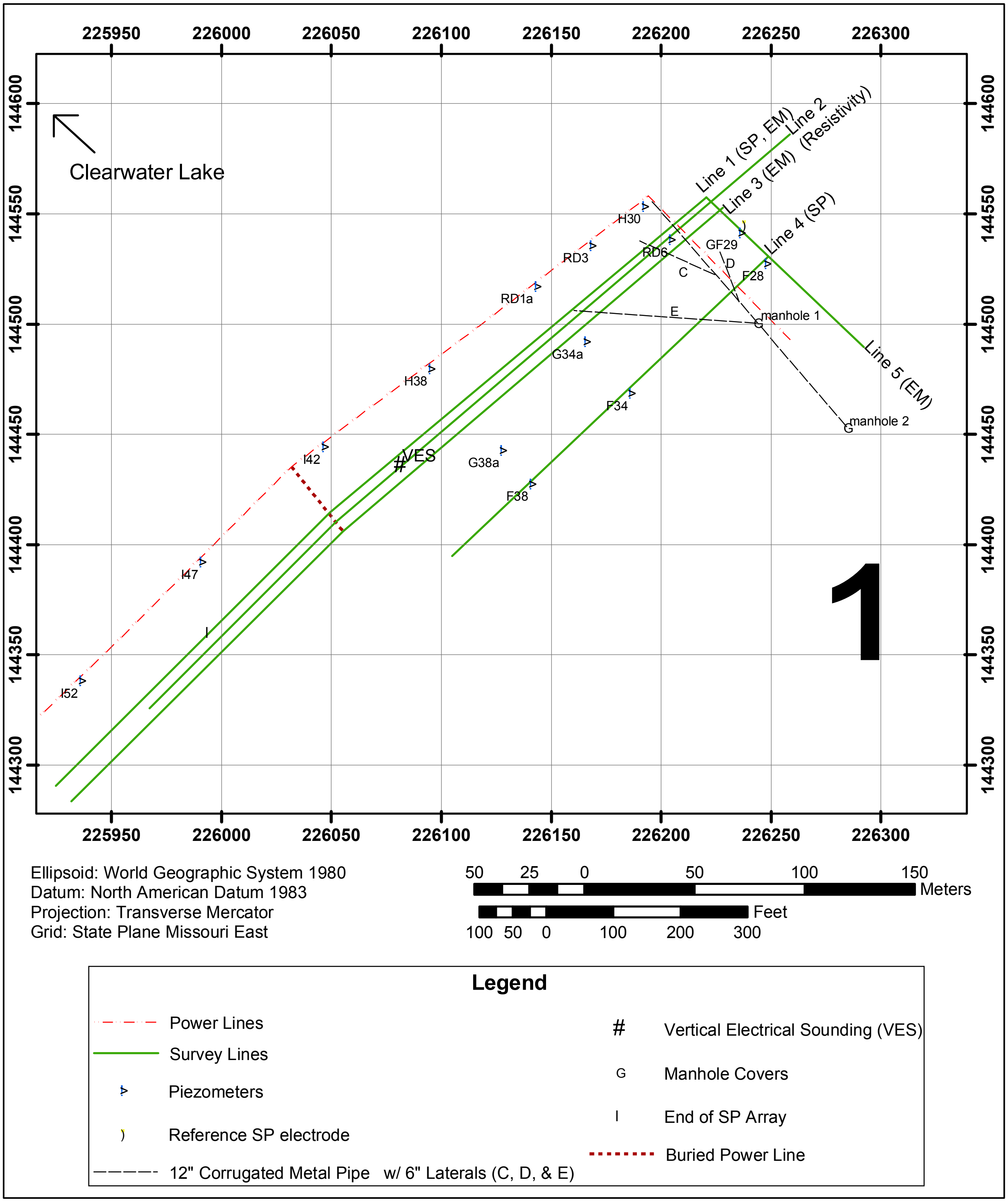

Figure 4. Geophysical test layout, Clearwater Dam, Missouri

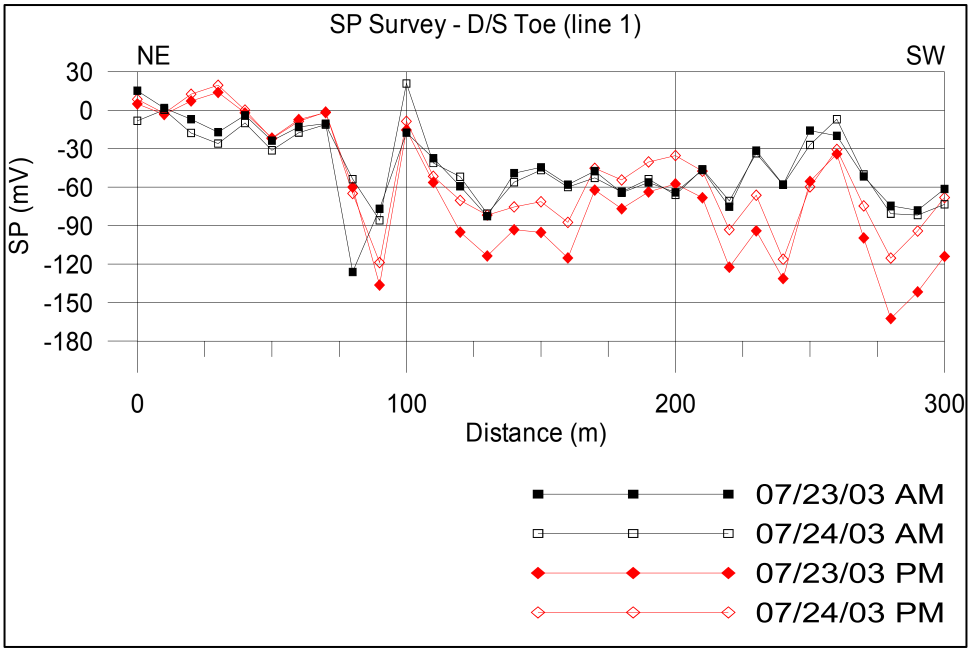

Figure 5. SP results, line 1

Electromagnetic profiling

Figure 6 presents apparent conductivity profiles, in millisiemens per meter (mS/m), from survey lines 1 and 3 for the EM31, EM34, and the GEM-2H (15,990-Hz) instruments. Inspection of the EM profiles confirms anomalies centered at stations 15 and 225 by all three instruments on both EM lines. Additional anomalies were located on line 2 centered over stations 340 and 360. The EM signatures recorded over station 20 are most likely related to the buried 12-in. (305-mm) drainage main, which runs in a southwestern direction and crosses the survey lines near station 20. The anomaly located at station 225 is attributed to a buried power cable originating from the power lines traversing parallel to the dam along an upstream abutment from the survey lines. Anomalies at stations 340 and 360 are most likely caused by shallow buried drainages related to the public bathrooms located just southeast of the survey lines.

Electrical resistivity profiling

The measured apparent resistivity values are first plotted in a 2-D pseudosection profile. Through mathematical inversion processes (using Res2dinv version 3.4), apparent resistivity values are calculated to create 2-D models that best represent the measured apparent resistivity values. Figure 7 presents an inversion model calculated from the dipole-dipole data set. This model represents one interpretation of the subsurface resistivity with root mean square (RMS) errors 36.1. The large RMS error value was unavoidable because of the geological site conditions (highly resistive sandy gravel fill), which caused high variations in the measured resistivity values.

Station 0 in Figure 6 corresponds to station 0 on survey line 1. The profile starts 45 m beyond station 0 (to the northeast) and extends 45 m beyond station 300 (to the southwest) in order to approximately cover the same cross-sectional area recorded by the SP array laid out along line 1.

The profile shown in Figure 7 presents pockets of lower resistivity values located between layers of higher resistivity. Most notable anomalies are the pockets of low resistivity centered at stations 0 and 50, indicating areas with increased clay and water caused by the 12-in. (305-mm) drainage main and 6-in. (152-mm) laterals ("C" and "E") crossing the survey line at stations 20, 30, and 75. There are notable highly resistive bumps along the lower portion of the profiles (approximately 10 m at depth) that correlate well with the known location of the limestone bedrock where the trough areas indicate joints or fractures in the limestone. Most of the low-SP anomalies noted along SP line 1 correlate fairly well with the pockets of lower resistivity noted along the dipole-dipole profile (i.e., 50, 90, 130, 160, 220, 280). However, these lower resistivity values (100 to 300 ohm-m) are too large to indicate just clay and water-filled pockets but could represent areas with mixed combinations of clay, sand, and silt materials at various moisture levels.

Electrical sounding

Results from the Schlumberger resistivity sounding are displayed in Figure 8 and show one 1-D interpretation model calculated from the measured values taken at station 185. The first layer with a thickness of approximately 0.3 m and a resistivity value of 240 ohm-m represents a sandy gravel layer. The second layer with a thickness of approximately 0.8 m and a resistivity of 1,100 ohm-m represents a layer of gravel to cobble-sized material. The third layer with a thickness of approximately 8.5 m and a resistivity value of 340 ohm-m was identified as a layer of finer sand and gravel with increased amounts of clayey materials. At a depth of approximately10 m, the resistivity values attain 1,275 ohm-m representing the top of the limestone bedrock, which correlates well with its known depth. Resistivity values, recorded at depth below station 185, between the 2-D and 1-D models, correlate well with a lower resistivity layer bounded above and below by a more resistive layer. Identification of geological variations below the limestone was indistinguishable from this sounding.

Case History Conclusions

A geophysical investigation was conducted along the toe of the Clearwater Dam in July 2003, to assess and locate possible seepage areas. The use of multiple geophysical techniques revealed many details about subsurface features. The ERDC geophysics team drew the following conclusions from the data:

a. The small negative anomalies (30 mV) along the SP survey line represent shallow seepage patterns within the sandy gravel fill.

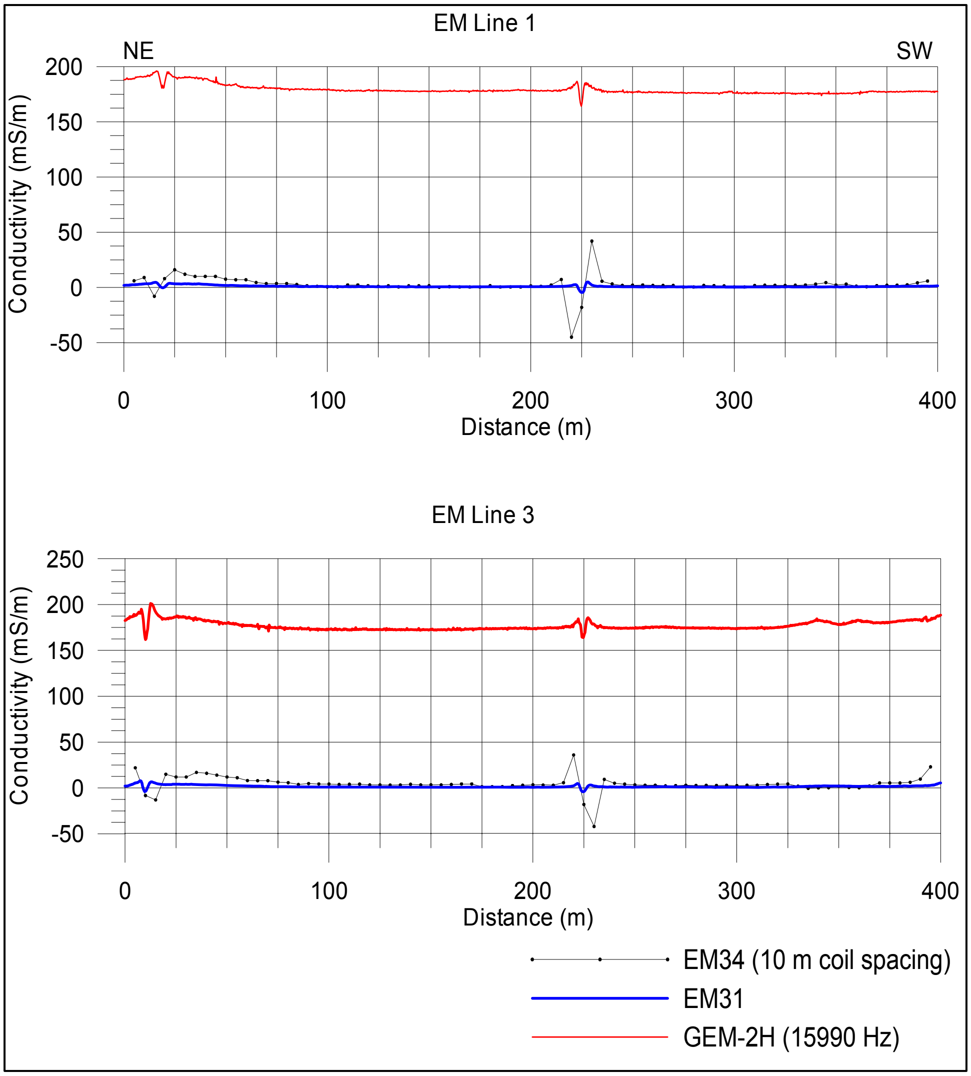

Figure 6. Comparison of EM31, EM34, and GEM-2H (15,990 Hz) results, lines 1 and 3

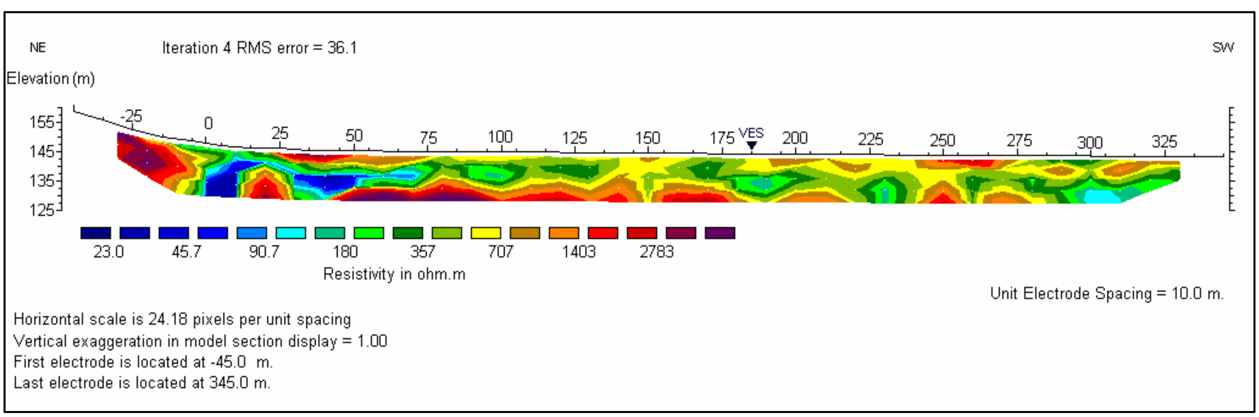

Figure 7. Inversion model from dipole-dipole array (horizontal distance and elevation are in meters)

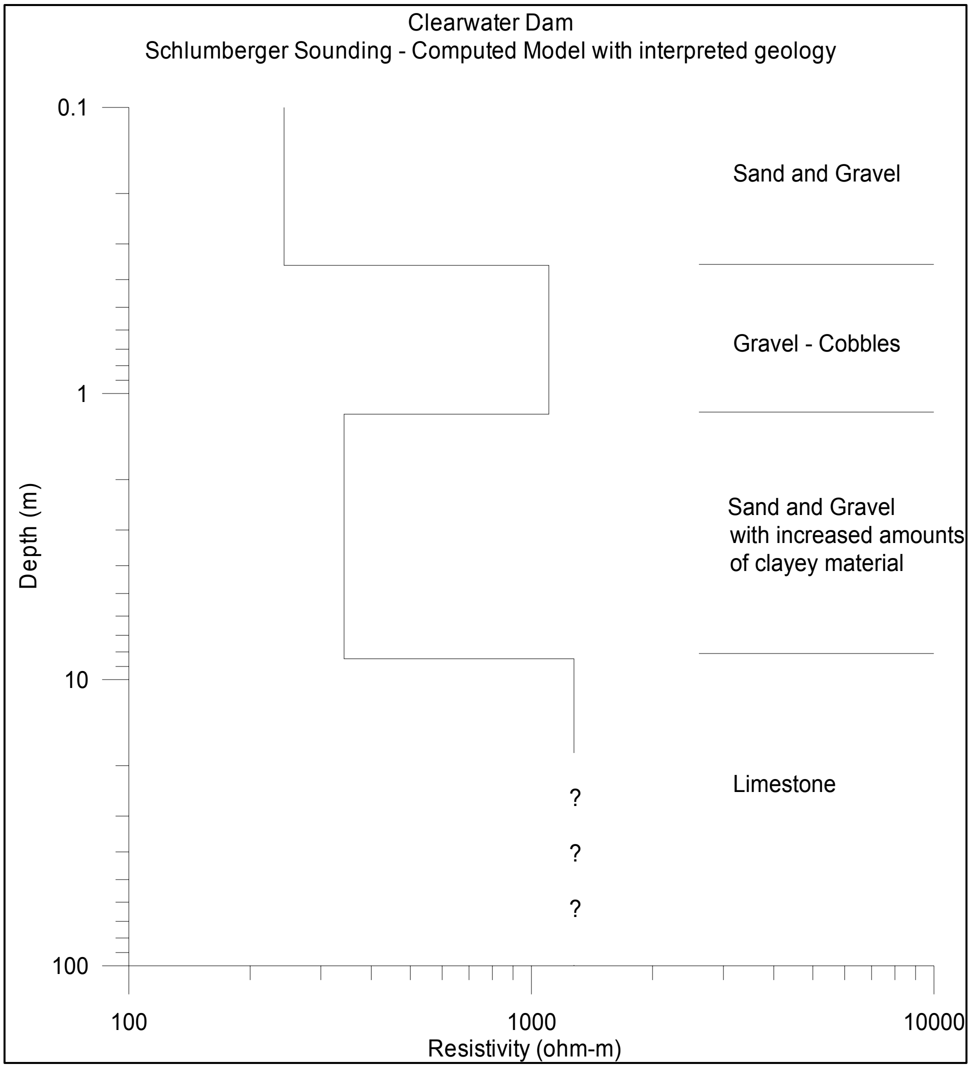

Figure 8. Resistivity sounding taken at station 185 along the resisitivity profile line

b. The most notable SP anomalies (up to 100 mV) occurring at stations 90 and 280 may be associated with a fault or fracture zone but do not appear to extend far beyond the survey line.

c. The SP negative anomalies located near stations 20, 35, and 90 are related to varying degrees of increased seepage caused by the 12-in. (305-mm) drainage line and 6-in. (152-mm) laterals where they cross the survey line near the above-mentioned SP negative anomalies located near stations 20, 35, and 90 related to varying degrees of increased seepage caused by the 12-in. drainage line and 6-in. laterals where they cross the survey line near the above-mentioned stations.

d. EM profiles exhibit notable anomalies along survey lines 1 and 3 and are attributed to the drainage system or power lines.

e. The resistivity profile presents pockets of low-resistivity values along the entire extent of the profile related to areas with increased clayey material.

f. The resistivity profile presents two notable low-resistivity anomalies at stations 0 and 50, indicating areas with increased clay and water seepage caused by buried drainage pipelines crossing the survey line near stations 20, 30, and 75.

g. The highly resistive peaks and troughs along the lower portions of the 2-D resistivity model indicate fractured/joint zones along the top of the limestone bedrock.

4 Summary and Recommendations

The above-mentioned case study illustrates how complementary geophysical methods can characterize and identify subsurface seepage areas as they relate to the bedrock fracturing, culturally emplaced drainages, and variations in soil type. Geophysical methods have been proven to detect, map, and monitor seepage areas within earthen embankments. Ideally, investigations should include complementary methods and should then be tied into existing borehole data to provide the best seepage characterization results. Geological data from the boreholes give a context to data interpretation by defining what geologic features are possible or likely. At Clearwater Dam, knowledge of the geology allowed interpretation of anomalies in light of fractures known to be present in the area. The geophysical data fell in the unknown zones between the boreholes, significantly reducing uncertainty about subsurface conditions and changes. What follows are recommendations for the most successful geophysical methods used in seepage assessment studies, that is, methods that show additional promise with further research and development.

The SP method has proven to be cost effective for seepage mapping and monitoring. Further research and development has made this method even more attractive for seepage monitoring studies. Past data interpretation techniques primarily have been qualitative. However, recent research described by Sheffer and Howie (2003) is developing modeling procedures so that the SP technique can be applied as a quantitative monitoring tool in seepage studies. With the new model, scientists are able to determine properties including hydraulic conductivity and flow rate as they affect the SP response. Numerical modeling was first introduced by Wilt and Butler (1990), using an algorithm developed by Sill and Killpack (1982). Sheffer and Howie (2003) presented preliminary 3-D models while incorporating the use of Visual MODFLOW, a commercially available seepage analysis software package, to provide a comprehensive seepage analysis. These modeled SP results, from a laboratory-scale embankment and a real-world earth dam (Mica Dam) in British Columbia, indicate that the SP method has potential as a quantitative monitoring tool. With further research and development, a multi-component SP technique could become a comprehensive investigation tool in seepage assessments.

Recent developments in interpretation software and data-collection instruments have improved the applicability of resistivity-profiling techniques for seepage studies. The amount of labor required for data collection has been reduced significantly with the introduction of newer instruments. Improved computer speed has provided inversion modeling tools within interpretation software for more meaningful, less ambiguous data interpretation. Resistivity methods also complement SP techniques and, when used together, these can provide an effective seepage assessment. Future research in 3-D resistivity surveys with emphasis on reducing data collection and processing techniques could make this method a much more economical and data-rich option for seepage investigations.

In summary, SP and resistivity (sounding and profile) methods are the most commonly used and successful techniques deployed on seepage characterization studies. However, other geophysical techniques including seismic, gravity, electromagnetic, and GPR should always be considered and used in conjunction with the primary methods, when possible, to provide the highest degree of confidence in identifying problematic areas and to reduce uncertainty about the subsurface. Geologic setting and cultural features within the study area need to be accounted for and considered when determining which geophysical methods to deploy for an investigation.

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14. ABSTRACT

The U.S. Army Engineer Research and Development Center (ERDC) Geotechnical and Structures Laboratory conducted a program of technical and archival research to document current knowledge of indirect seepage detection and methods for monitoring the conditions within small embankment dams. This report documents current methods used to determine conditions within embankment dams by indirect means and provides guidance on determining which methods will most likely succeed at various sites. The report includes a review of current indirect geophysical technologies used in seepage investigations with emphasis on small-sized earthen dams (<7,500 m long, <40 m high). A summary of state-of-the-art equipment, principles of operation, and field procedures is also presented, followed by the results of a September 2003 geophysics-based investigation of seepage and conditions within Clearwater Dam in southeastern Missouri. The report concludes with recommendations for future development of the most promising technologies to be used for seepage detection and assessing the condition within embankments.

15. SUBJECT TERMS

Clearwater Dam	Electrical resistivity	Near-surface geophysics
Dam condition assessment	Embankment dam	Self-potential

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